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Assessing CCS viability - A socio-technical framework

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Abstract

This paper develops an interdisciplinary framework to assess the different dimensions of uncertainties which surround the development of carbon capture and storage (CCS). It includes technical, economic, financial, political and societal uncertainties about CCS and develops methods for assessing these uncertainties. It also identifies important linkages between uncertainties. This generic framework aims to help decision making on CCS by private and public actors. The paper is based on a systematic review of the social science literature on CCS and on broader insights from innovation studies.

Keywords: CCS; technology assessment; uncertainties

1. Introduction

Carbon Capture and Storage (CCS) is nowadays often considered a crucial technology in the long term carbon abatement strategies of many countries and international organisations. However, despite its potential, the technology has yet to be proven as an integrated system at a full-scale and there is uncertainty – and contestation – about CCS in terms of its maturity, viability and potential impacts. While CCS is seen as vital by some actors, others claim it is not an attractive option and may not be a necessary part of the transition towards a low carbon economy [1]. This highlights the need for a method for assessing the multiple uncertainties associated with CCS. Technology Assessment (TA) is an interdisciplinary, future-oriented analysis of emerging technologies which scrutinises their (only partially knowable) nature and possible impacts (see section 2).

While CCS is now entering a phase of demonstration of full scale integrated systems in various locations around the world [2], there are still significant technical, economic, political and financial uncertainties about CCS. This creates challenges for those actors who want to see CCS technology developed and deployed. For example, this is a problem for policy makers designing policy for CCS as well as broader energy and climate change mitigation. This is crucial as CCS will need government support to be part of the mitigation mix [3, 4]. Such policy support should be as well informed as possible. Uncertainty is also problematic for businesses that need to take decisions in terms of investment choices [5, 6]. This paper makes a contribution to these debates by providing an assessment framework

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that identifies key uncertainties of future CCS development as well as methods to assess these uncertainties. This framework aims to help systematic decision making on CCS by private and public actors.

A growing social science literature on CCS has developed over recent years which points to a number of important uncertainties around the development of CCS. Our paper systematically reviews this literature and draws on broader insights from innovation studies shedding light on the development of technologies more generally. The research questions of this paper are:

1. What are the main uncertainties with regard to future CCS development?
2. How can these uncertainties be assessed (quantitatively or qualitatively)?
3. How are the different uncertainties inter-related (synergies and trade-offs)?

By addressing these questions, the paper will develop a draft assessment framework for CCS technology viability and maturity. By engaging with the wider TA literature, we also hope to contribute to the development of TA more generally. By describing the gaps in social science research on CCS, we will also contribute to that field of research.

This paper draws on a recently started research project funded by the UK Energy Research Centre. The project will provide an independent assessment of the viability of CCS in the UK from now until 2030. This paper is the preliminary output of the first stage of the project.[2]

The next section of the paper will provide a brief review of the relevant literature on technology assessment and presents an overview of the limited existing social science research on CCS innovation. The third section will outline the methodology used. Section 4 provides the analysis and results and section 5 concludes.

2. Technology Assessment (TA) and the existing social science literature on CCS

This paper relates to two existing bodies of research: that on technology assessment (TA), and social science research on CCS. This section will position the paper in relation to the broad field of TA, and demonstrate its main novelty which is the application of a novel assessment framework to CCS technology.

TA as a programme of action was initiated in reaction to the growing critique of the effects of modern technology in the 1960s. Classic TA [7] was focussed on forecasting technology change so as to predict its impacts on society. It aimed to support the development of policy managing those impacts, and was organised in advisory bodies like the Office of Technology Assessment in the US [8]. The inherent difficulties of this task meant it worked best for specific and relatively mature technologies [7]. Critiques have been levelled against the typical, often implicit, assumptions in classical TA about an autonomous and inevitable direction of technological change, assumed to be independent of society [9].

A second wave of TA work in the 1980s and 1990s [7, 10, 11] instead started from the realisation that technology is generated and shaped by the people and institutions involved in its development. Technology was seen to co-evolve with the development of society. This brought an emphasis in TA activities on deliberation and involvement by a broader range of actors [12]. The professed stance of TA also changed from distanced observation to involvement with technology development and technology governance, and from forecasting to a more modest insistence on iterative, continuous assessment. This paper draws on this later TA tradition.

A systematic review of existing social science research on CCS reveals that it has so far focussed on two main areas. Firstly, there are publications exploring public understanding and acceptance [13]. Secondly, there is work based mainly in economics, particularly the modelling of deployment scenarios and assessments of the impact and cost efficiency of CCS and other climate mitigation options. These literatures will be reviewed in more detail below.

There is only a small social science based literature that is more directly concerned with CCS innovation and technology development. There is some research on learning curves [14, 15]: quantified models of technology costs that are usually forecast to decline as a function of deployed capacity. These studies are intended to measure technology learning and improvement in the form of decreased costs. But in the absence of reliable CCS cost data, they are reliant on inferring lessons from cost trends in other technologies, for example Flue Gas Desulphurisation technology. When applied to CCS, such models also rely on very uncertain assumptions about current CCS costs. Ultimately, learning curve analysis can only tell us a limited amount about CCS innovation processes.

[2] It is important to stress that this paper is merely an illustration of our approach and should not be taken as the final output from the first stage of the project since the framework is still 'work in progress'. Due to the preliminary nature of the work, please do not cite without permission from the authors. Financial support from the UK Research Councils is gratefully acknowledged.

There is also a limited literature on CCS innovation systems [e.g. 16, 17], which has begun to explore the role of actors and institutions. A key result of this research is that the CCS innovation system is comparatively well developed in terms of – mainly academic – knowledge creation and diffusion, as well as with regard to the development of visions for the technology that can guide the activities of the involved actors. In contrast, the creation of a market for the technology is weak. In international comparison, Norway stands out as a country with a long history of CCS engagement and a more strongly developed innovation system. However, innovation system studies tend to downplay the political aspects of what goes on in innovation processes. Relatedly, they take the technology as such for granted, and do not necessarily question its basic desirability, definition and function.

There is thus plenty of scope for analysis and assessment of actual and potential CCS innovation that takes a broad view across technical and social aspects and uncertainties of CCS technology. In the next section we will set out an approach to the assessment of CCS technology that will contribute to this.

3. Methodology

This research is designed in the vein of modern TA (as described above) in several ways. It deals with both apparently technical and social factors together, as co-evolving phenomena [18]. It engages with technology in the development stage, through collaboration with CCS scientists and engineers in academia and industry. It includes deliberation and involvement of a wide range of stakeholders through the project steering group. This research cannot in itself provide continuous assessment, but will deliver an assessment framework that will need to be applied iteratively and adapted as new knowledge about CCS development becomes available.

In line with lessons from TA, as reviewed above, this research does not aim to support forecasting of the development of CCS technology. The progress of CCS will clearly depend on what relevant actors do in the innovation process. Even the properties of the technology will be shaped by the actors and thus determined in the evolving innovation process. This means that CCS can only be predictable to a limited degree, and that no assessment method can reveal a real CCS future. The point is not to provide best guesses about any "real" CCS future, but rather to know what the key uncertainties are and how to asses them, so as to monitor the development of the uncertainties and be able to prepare for multiple possible futures.

In order to put together the assessment framework, key uncertainties of CCS development and deployment until 2030 were identified. The research here draws on insights from existing social science literature on CCS and other technologies. It also benefits from input from the interdisciplinary project group, including also geology, engineering, legal and financial expertise, and consultation with CCS stakeholders represented on the project steering group. The resulting list of key uncertainties for CCS innovation can be seen as part of the table in section 4.2 below.

A literature review was undertaken to establish what is known about these key uncertainties from a social science point of view, as well as more fundamental insights about how to conceptualise and understand them. Social science on CCS was inventoried, to review what is known about the uncertainties. This was done in June 2010 using the Web of Knowledge. Combinations of the terms 'CCS', 'CO_2', 'carbon' capture', 'sequestration' and 'storage' were used. Having excluded papers that are not relevant (e.g. because they were purely technical or only mentioned CCS in passing) a set of 74 social science (including economics) papers resulted. This enabled the review of some of the CCS uncertainties, for example public understanding, as they have been more extensively studied by social scientists. Where there is little social science research, for example on system integration, general innovation studies literature was used in order to see what it would tell us for the case of CCS. An objective of this research is to support decision-makers needing to assess CCS viability and maturity. Therefore, the literature reviews also investigated indicators and (qualitative and quantitative) methods that can be used in assessments of the uncertainties identified.

Scholars usually focus on a particular uncertainty (e.g. public acceptance, see [19] or costs, see [20]) instead of looking at CCS uncertainties across the board and their interactions. However, as the uncertainty dimensions studied are not independent, synergies and trade-offs were also identified. By synthesising insights from the existing literature on CCS as well as more general insights from innovation studies into how large-scale, complex technologies develop across the range of key uncertainties a contribution is made which goes beyond the state of the art.

4. Analysis and results

This section provides a short description of the main uncertainties identified (4.1). It briefly summarises the key insights from the literature into the nature of these uncertainties and how they can be assessed (4.2). The final part of this section looks at some of the inter-linkages between uncertainties (4.3).

4.1. Important uncertainties about the future development of CCS

Uncertainty 1: ‘Variety of CCS pathways’ There is technological diversity for each of the components of the CCS chain – for example in types of capture, in modes of CO_2 transport, and in types of storage facility. Competition among technologies is normal and good for learning, but will most likely be reduced as we get nearer wide deployment. There is uncertainty as to what technologies will win out, and when that will happen. This raises dilemmas for the relevant actors (investors, government, etc.) in terms of what technologies to invest in at different points in this development. Early selection may get outdated quickly, stranding actors with uncompetitive assets, and/or locking CCS into inferior technologies. Governments need to balance the need for experimentation with the need for fast development and deployment and perhaps premature closure of the technological choices.

Uncertainty 2: ‘Safe Storage’ One of the key uncertainties with CCS is whether storage will prove to be safe over long periods of time. While some of the components of CCS have been applied in industrial settings, geological carbon storage represents new challenges. The storage risk has two dimensions: local environmental, health and safety risks and the global risk of carbon dioxide re-entering the atmosphere undermining climate change goals [21]. There is uncertainty about probabilities and risks and a lack of experience with geological storage by developers, regulators and researchers. These risks vary across storage options and settings. Developing appropriate (e.g. credible and long term) risk governance mechanisms is therefore essential for the deployment of CCS to be successful.

Uncertainty 3: ‘Scaling up and speed of development and deployment’ CCS should ideally be ready for implementation within the next decades. This includes having the required knowledge, but also the skills, industries, institutions, etc. Key technologies also need to be scaled up. The complexities involved include if and when we will see dominant designs emerge; how much competition there will be among competing technologies (capture variants, storage options, etc.), and if components can be developed and scaled independently of each other. There is a need to know how we can assess whether development and up-scaling will be possible and if it can happen fast enough. It is also of interest to assess if and how top-down, government steering could speed this up.

Uncertainty 4: ‘Integration of CCS systems’ CCS exists today as sets of components, types of expertise, etc. Integrating these into working CCS systems raises technical issues, for example limiting the impurity concentrations allowable for transportation. It also brings social challenges in terms of coordinating the actors that are developing and operating CCS systems. These technical and social aspects are likely to be related [22]. System coordination is also complex in that the different activities involved (operation of CCS systems, supporting R&D, verification of sequestration for CO_2 trading, etc.) will likely require different modes of coordination and organisation. Also, coordination may differ at the component vs. system levels. Possible models of coordination of CCS development and operation vary with regard to the degree of market orientation, centralisation, fragmentation, participation, etc.

Uncertainty 5: ‘Economic and financial viability’ One of the key uncertainties of CCS is its future economic and financial viability for investors. A technology is economically viable if it has a positive cost-benefit ratio. Even if a technology is economically viable, that does not necessarily mean that it is financially viable because it may have associated risks which make it less attractive than investing in alternatives [23]. Economic and financial viability is a key uncertainty for businesses as well as policy makers and will determine their willingness to invest in CCS. Improving the economic and financial viability is an important rationale for policy support.

Uncertainty 6: ‘Policy, political and regulatory uncertainty’ Uncertainty about CCS development is not only due to economic or technical but also political factors. In this context, policy (specific policy instruments which could help CCS to develop) as well as politics (the political processes of getting acceptance, legitimacy and continued support for CCS, questions of power, lobbying, etc) are important. There is also uncertainty about crucial regulatory issues (incl. questions of liability, safety rules, etc). These factors are important because in part the future development of CCS will depend on explicit political and policy choices as “a strong regulatory push and/or a significant price for carbon emissions will be required to develop commercial applications” [24: 9].

Uncertainty 7: ‘Public acceptance’ Another key uncertainty around the development of CCS is whether CCS will be seen as a legitimate technology for climate change mitigation. The existing literature stresses that societal acceptance is widely recognized as an important factor influencing the successful development and diffusion of new technologies [25-27]. However, there are also examples, like genetically modified organisms, where public resistance has failed to stop the technology (in the US). Public acceptance is not just a matter of individual preferences, but the results of social interactions.

4.2. Key insights into the uncertainties and their assessment

The following table summarises the key insights gained from the literature reviews. It also lists possible indicators and methods that can be used in assessments of them.

Table 1: Key insights into uncertainties and their assessment

	Key insights	**Indicators and assessment methods**
1. 'Variety of pathways'	- Need for policy supporting technological diversity to maximise learning and the chances of constructing good technology / avoiding lock-in to poorly performing technology. - This should be weighed against early selection and resource prioritisation, which might help accelerate development. - A commercial breakthrough with one CCS variety would not in itself establish a dominant design, but therefore also not necessarily lead to lock-in.	- Market share of technology variants - Error in market forecasts - Capital intensity - Lead time - Interrelatedness to other technologies - Accumulated experience (years) - Expectations of key actors about future investments
2 'Safe storage'[3]	- Long term storage costs and risks pose issues for intergenerational equity. - Uncertainty about suitable long term risk assessment and governance frameworks (e.g. regarding long-term liabilities). - The perceived risks of leakage are an important concern of the public.	- Leakage probabilities and rates (may be hard to quantify; will vary by site). - Public risk perceptions of storage - Expert consensus on storage safety - Existence of clear risk assessment and storage governance arrangements
3. 'Scaling up and speed of development and deployment'	- Up-scaling is not trivial, and requires investment, engineering skills, time and organisation. - Information exchange and working in parallel on different development stages may help speed up development. - Up-scaling may fail. Trajectories may end, unpredictably. - Trade-off between 1) speed and large scaling steps and 2) risk of failure and poor quality outcomes. - It may be too early for scale-up, given the short development history and lack of dominant design. - Establishment of clear performance criteria for CCS systems and components is important.	- Change in performance and size of demos over time. Maybe possible to model this, when enough data available. - The emergence of reference facilities - Whether performance criteria and standards have been established
4. 'Integration of CCS systems'	- Unclear situation re how to organise and coordinate CCS systems, with different components, supply chains, types of expertise, etc. - Unclear to what extent innovation can/will be planned centrally, or emerge through market experimentation, and who will have the integration capabilities. - It seems likely that standardised components/interfaces will facilitate CCS system integration	- Public or private management - Managed in one organisation or distributed. Degree of collaboration along chain - Development of standardised interfaces between components - Technocratic management vs participation. - Actors with system integration skills

[3] Note that the analysis of this uncertainty is still ongoing and results here are only tentative.

5. Economic and financial viability	- Little empirical data so far; no studies that measure CCS cost reduction (learning) directly are available. - Heavily influenced by political factors and policy frameworks, e.g. carbon trading schemes/carbon pricing. - Cost estimates are influenced by uncertainties in: fuel reserves and prices, electricity prices, capital costs and load factors. - Increased experience in deploying a technology may make it cheaper. However, some energy technologies have become more expensive; there is a danger of 'appraisal optimism'. - Risk is important for investment decisions, not just costs; policy uncertainty creates risk premium.	- Reported project costs - Expert elicitation, particularly on financial risks - Scenarios - Learning curves - Modelling - Empirical observation of other capital intensive technologies (e.g. offshore wind, nuclear, conventional coal, FDG etc) to draw analogies
6. 'Policy, political and regulatory uncertainty'	- Regulatory frameworks are often lacking, are highly fragmented or in the early stages which contributes to uncertainty for potential investors. - Major uncertainties around liability and ownership issues. - Current policy frameworks (e.g. EU ETS) are not sufficient; additional instruments will be needed to encourage investment; uncertainty about what is the 'best instrument'. - In some countries CCS is a contested part of the climate policy mix which creates uncertainty. - However, the dominant framing of CCS as one important option in the mitigation portfolio is judged to be reasonably robust, enjoys widespread support in international climate and energy policy circles and appears to broaden the coalition in favour of long term climate mitigation efforts.	- Framing of CCS as a major contributor to carbon emission mitigation in government strategy - Absence of political contestation of CCS among relevant societal actors - Existence of an elaborate, CCS-specific regulatory regime (e.g. covering licensing and liability) that is also coherent (one stop-shop or distributed responsibility) - Existence of a high and consistent carbon price/tax - Existence of a suitable, long-term and coherent instrument mix
7. 'Public acceptance'	- A number of studies show that stakeholder attitudes (cf public) are often moderately positive - Public acceptance often depends on information from media and stakeholders - Trust in key institutions is of key importance. Judgement often based on perceived competence, intentions and value similarity. - Factors that may foster acceptance include: participation with real influence on projects, offering additional benefits may help, simultaneous support to other low carbon options, better understanding of climate mitigation rationale - NIMBY-ism can become a problem in relation mainly to onshore pipelines and storage.	- Public and stakeholder attitudes - Activity of lobby groups - Media presentation of CCS - Questionnaire-based surveys/ Information-choice questionnaires - Qualitative, in-depth interviews - Focus group discussions/citizen panels - Stakeholder workshops - Analysis of written reports of stakeholder groups - Psychometric analysis of risk perception of CSS

4.3. Inter-linkages between uncertainties

After having identified a set of important uncertainties in developing CCS, it is essential to look at inter-linkages between these uncertainties. This helps us identify possible synergies and trade-offs between uncertainties which is important information for public or private decision makers on CCS, since any efforts to reduce or manage one uncertainty may have effects on others. The diagram below aims to depict some of the important inter-linkages.[4]

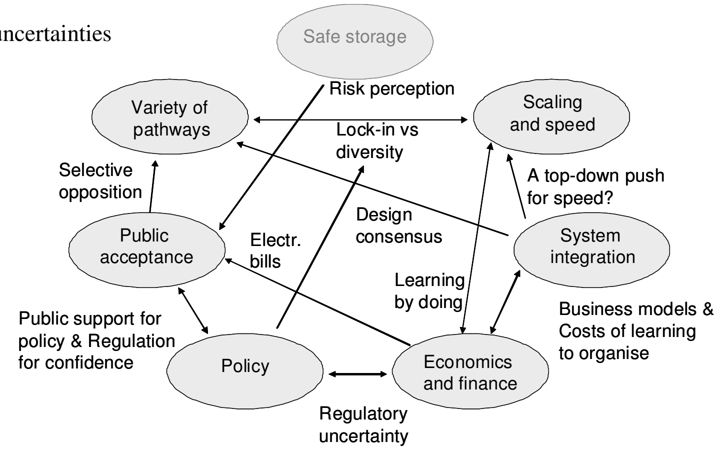
The analysis yielded a variety of important linkages between uncertainties, which are summarised below:

- Political, policy and regulatory decisions about policy support, carbon prices, carbon reduction goals, liability rules, possible inclusion in CDM and EU ETS, etc. massively impact on the economic and financial viability.
- The absence of credible regulatory regimes can decrease public confidence and can provoke opposition; a strong regulatory regime might give stakeholders confidence and increase public support. Public acceptance may be necessary for political support, and impacts on policy and regulatory decisions.

[4] Note that the analysis for the dimension 'safe storage' has not yet been completed.

- Selective opposition to some variants (e.g. onshore storage) may decrease the variety of options available.
- Quick up-scaling risks locking-in to poor technology by reducing variety too early; conversely exploring a variety of different pathways risks spreading the resources too thinly. Policy and regulation will impact on this.
- Storage risk perception is central to public acceptance.
- Different governance and business models may impact on the speed and viability of development and up-scaling. A top-down push may increase speed, but also increase risks of technology failure.
- A strong top-down coordination of the CCS community could facilitate consensus about design choices.
- Learning by doing can help reduce costs. Lowered costs will stimulate investment and thus learning.
- Different business models for handling financial risks may fit best with different ways of integrating CCS systems. Learning how to integrate and coordinate CCS systems may be costly.
- Publics may resent the added cost of abatement; CCS cost improvements presumably will improve the societal acceptability of the technology.
- Uncertainty about future costs of CCS makes it difficult for policy makers to make decisions about the importance of CCS in the climate change mitigation portfolio compared to other options.

Figure 1: Interlinkages between uncertainties



5. Conclusions

The paper presents a draft 'assessment framework': insights regarding key CCS uncertainties, how they can be assessed and how they inter-link. Its novelty lies in the treatment of the range of different uncertainties together, reflecting the inter-related nature of technical, economic and social aspects of CCS innovation. The paper also makes a contribution by synthesising insights from social science literatures on CCS and innovation. Several of the uncertainties identified – e.g. system integration, the politics around CCS and diversity of pathways – have not received much social science attention and therefore offer the most scope for novel contributions in future research.

We think the suggested assessment framework is of interest to decision makers needing to assess the viability and maturity of CCS technology. The framework draws on lessons from and should be relevant for the assessment of other technologies. It is likely to be relevant for assessment of primarily low-carbon or environmental technologies, and other large, complex process technologies.

Subsequent stages of the project will include the application of the framework developed in this paper to a number of historical case studies of technologies which are partial analogues to CCS for specific uncertainties. The final step of the project is to develop a set of pathways for future CCS development, and to apply the framework to these. A key output of the pathways analysis will be sets of criteria and milestones against which CCS development can be assessed now and until 2030.

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